Grant Title: **3-D Coronal-Solar Wind Energetic Particle Acceleration (C-SWEPA) module**
2nd Year Progress Report
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I. C-SWEPAObjectives:

The 3-D Coronal-Solar Wind Energetic Particle Acceleration (C-SWEPA) modules provide tools for taking the critical next step in understanding Solar Energetic Particle (SEP) events and characterizing their hazards through physics-based modeling *from the low corona through the inner heliosphere*. *C-SWEPA's central objective is to develop and validate a numerical framework of physics-based modules that couple the low corona and CMEs with solar wind, shocks, and particle acceleration.* Simulated observers (e.g., spacecraft near L1, Earth, moon, Mars, etc.) provide basis for comparison with spacecraft and tools to explore simulated mission datasets (e.g., Solar Probe Plus, SPP, and Solar Orbiter, SolO).

C-SWEPA fulfills the need for a transformative synthesis of LWS capabilities by bringing together an exceptional team of leading experts from five institutions in solar, heliospheric and magnetospheric physics and two successful LWS strategic capabilities: the Earth-Moon-Mars Radiation Environment Modules (EMMREM), and the Next Generation Model for the Corona and Solar Wind. C-SWEPA leverages new advancements in High Performance Computing (HPC) through the use of heterogeneous architectures (Graphical Processing Units; GPUs) and develops an innovative approach to delivering complex models that enables the CCMC to use dedicated GPU-enabled and massively parallelized systems for C-SWEPA simulations.

C-SWEPA is a transformational project providing: an integration between observationally-driven modeling of CMEs, solar wind, shocks and energetic particles from the low corona through the heliosphere; incorporation of seed populations and associated compositional dependencies; and detailed models that probe the steady and disturbed corona thus paving the way for SolO and SPP studies.

C-SWEPA deliverables include: two numerical systems (one at the CCMC and one at UNH) that run C-SWEPA; documentation; and an intuitive interface. These systems provide: on-line availability and event scenarios from Sun-to-Earth; runs that include solar wind, CMEs and associated shock(s), SEP flux time series, dose & dose-equivalent rates, integrated doses behind various layers of shielding; and results of runs made for specific campaign events of interest to the science community at large. Both EMMREM and CORHEL run at the CCMC and the associated teams have a strong history of partnering with the CCMC.

C-SWEPA answers fundamental scientific questions that study the corona, solar wind, CME initiation, shocks, solar energetic particle acceleration and propagation. Core team members have experience working together and leverage developments from CISM, EMMREM, CORHEL, NSF's FESD Sun-to-Ice project, and existing Focus Science Teams (FSTs) of NASA's Living With a Star (LWS) Program.

C-SWEPA provides broad impacts by advancing discovery and understanding while also promoting teaching, training of graduate students, undergraduate involvement, and participation of under-represented groups. C-SWEPA enhances the infrastructure for research and education through development of computing capabilities for the science community. By advancing tools for understanding and predicting space weather, C-SWEPA provides important societal benefits enabling expansion of space technologies.

Currently, C-SWEPA has completed its first milestone in modeling a single event Sun-to-Earth. One paper has been published on the event and several are in work. The team is ramping up focus on the second milestone of a coupled models that runs at the CCMC. The project is ahead of schedule.

II. C-SWEPA Accomplishments:

II.1 C-SWEPA Progress in Understanding of Protracted Minimum of Cycle 23/24 and the the Mini Maximum Cycle 24

The deep solar minimum between cycles 23 and 24 and the activity in cycle 24 differed significantly from those of the prior cycle (Schwadron et al., 2011; McComas et al., 2013). In the solar minimum, the fast wind was slightly slower, was significantly less dense and cooler, had lower mass and momentum fluxes (McComas et al., 2008), and weaker heliospheric magnetic fields (Smith et al., 2008). During the rise of activity in cycle 24 the mass flux of solar wind remained low, (McComas et al., 2013b) and the magnetic flux of the heliosphere remained at significantly lower levels than observed at previous solar maxima in the space age (Smith et al., 2013). (McComas et al.,, 2013b) showed that the current "mini" solar maximum of cycle 24 has shown only a small recovery in particle and magnetic fluxes. Therefore, the cycle 24 mini solar maximum continues to display the same trends as observed in the cycle 23-24 minimum. In fact, conditions during the cycle 23-24 minimum appear to be similar to conditions at the beginning of the 1800's at the start of the Dalton Minimum (Goelzer et al., 2013). Taken together, these recent changes suggest that the next solar minimum may continue to show declining sunspot numbers, associated with declining values of magnetic flux and further reductions in solar wind particle flux.

Using the model from Schwadron et al. (2010) and monthly average sunspot numbers, Goelzer et al. (2013) were able to compute a monthly average HMF intensity from 1749 to the present. For comparison, Goelzer et al (2013) looked at the work of McCracken (2007), who modeled the HMF intensity from the levels of paleogenic nucleotide ^{10}Be and the Omni2 data, which is available back to 1963. These three estimations of flux as well as sunspot number are shown in Figure 1, with a strong correlation and a clear hysteresis.

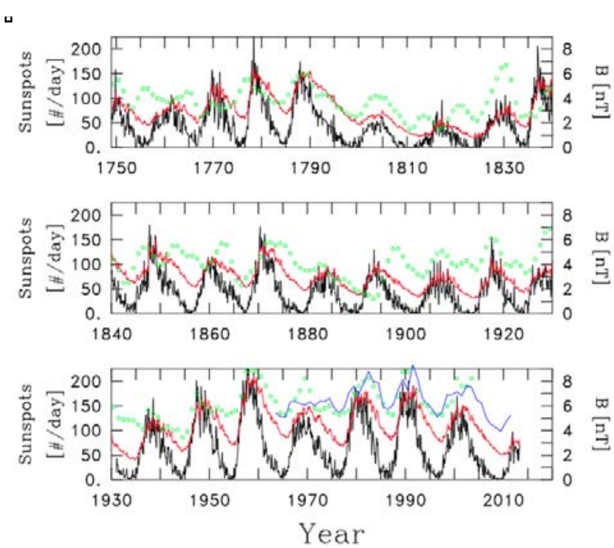

Figure 1: *(black) Monthly ave SSN. (red) Predicted Parker comp. of the HMF intensity. (green) Yearly ave HMF intensity derived from ^{10}Be data. (blue) Measured yearly aves of HMF intensity (Smith et al. [2013]) from the Omni2 data.*

The anomalously weak heliospheric magnetic field and low solar wind flux during the last solar minimum have resulted in galactic cosmic rays (GCRs) achieving the highest flux levels observed in the space age (Mewaldt et al., 2010), and fluxes continue to be unusually elevated through the cycle 24 maximum. It is unknown if the recent anomalous deep solar minimum hints at larger changes in the near future, or if the unusual changes in GCR fluxes and conditions on the Sun have an impact on Earth's atmosphere. Given the fact that GCR radiation can damage living tissue, causing cellular mutagenesis, the changing state of the Sun may have long-term implications for life on the planet. Figure 2 illustrates the critical growing record of dose rate throughout the LRO mission that quantifies the changing conditions and radiation hazards posed by GCRs and SEPs. Pronounced discrete SEP events punctuate the underlying trend of diminishing long-term GCR doses.

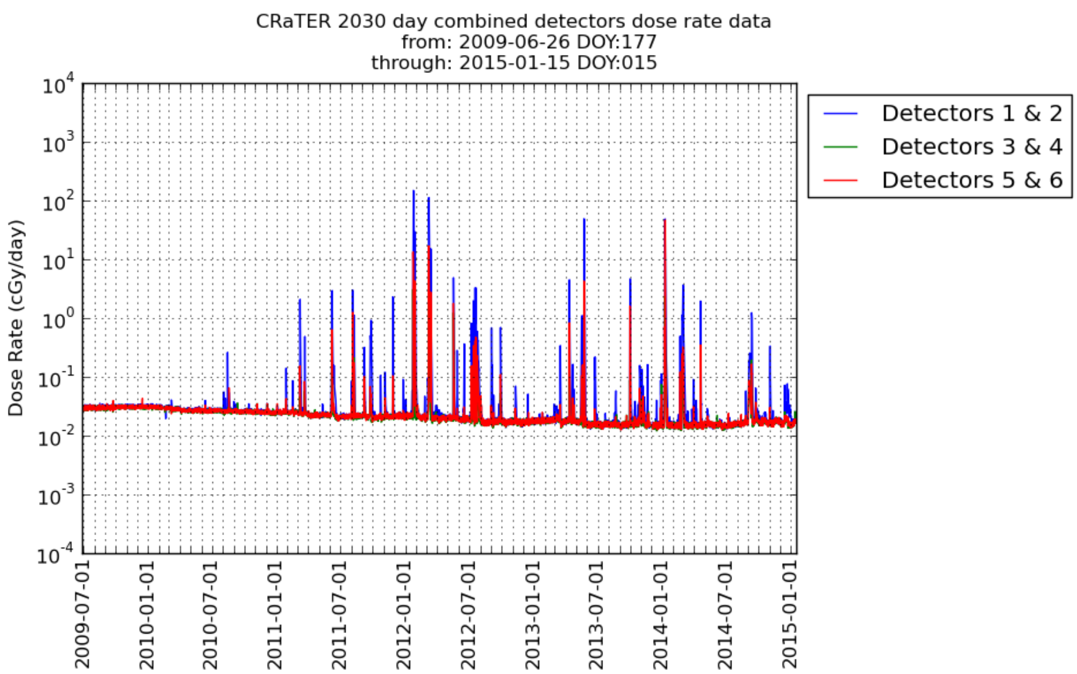

Figure 2. *Dose Rates over time through the quantify radiation hazards that damage tissue, materials, and chemically change materials such as lunar regolith.*

Figure 2 reveals SEP events consistent with a double-peaked solar cycle. We further observe that the underlying GCR dose rate is now on the rise and has been rising since July, 2014. It would appear that the solar cycle 24 maximum is complete and the heliospheric modulation of GCRs is diminishing as we move toward the cycle 24-25 solar minimum.

The extremely high energies of GCRs make them both relevant to biology on the Earth, and also one of the greatest hazards for long-term space exploration. In deep interplanetary space and away from the shielding of Earth's atmosphere and magnetic field, these high energy particles are difficult to shield against, as some particles surpass a billion electron volts of kinetic energy. The effects of GCRs on the Earth system, including the biosphere, remain poorly understood and are oftentimes highly controversial (Shaviv and Veizer, 2003); this is because GCRs not only present a hazard to life through the breakdown of DNA, but also may help to stimulate evolution by increasing the rate of cell mutation (Todd, 1994). For example, a recent study of global diversity from paleontological data suggests there is a significant cycle of approximately 62 million years over which biodiversity rises and then falls; this cycle as of yet has no agreed upon cause but may be driven by extraplanetary processes (Rohde and Muller, 2005).

Schwadron et al. (2014a) used results of CRaTER, C-SWEPA, PREDICCS and EMMREM to understand implications of the changing space environment for human exploration. Several key results are shown in Figures 3 and 4. Figure 3 shows the evolution of GCR dose over time based on C-SWEPA and EMMREM modeling and data from CRaTER and ACE. The implication of the weakening interstellar magnetic field is that the observed dose rates at successive solar minima and successive solar maxima have been increasing with time. It remains to be seen whether these changing conditions will persist. The latest trends demonstrate that the space environment is becoming increasingly hazardous and present a limiting factor for human exploration beyond LEO.

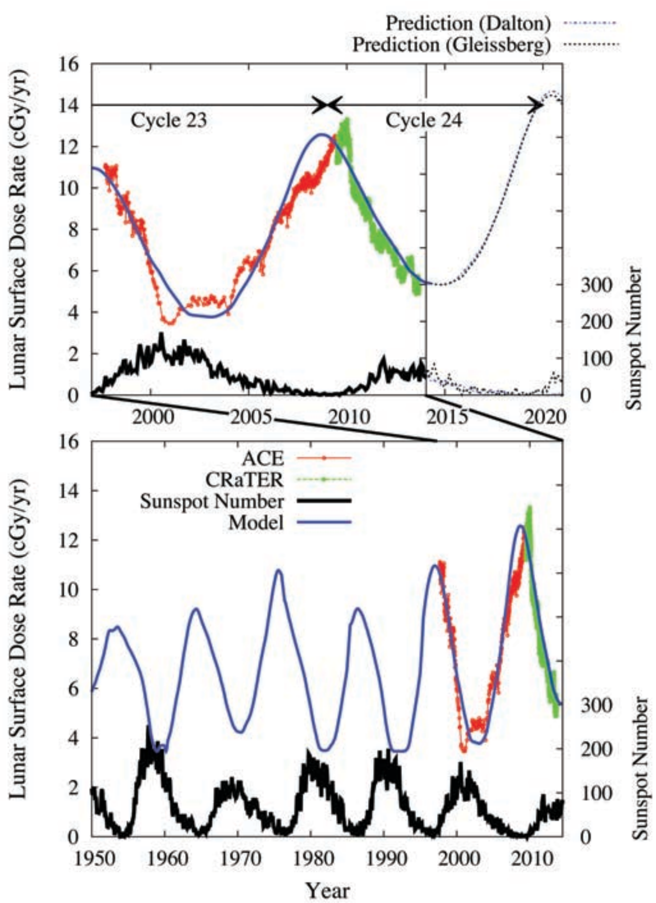

Figure 3. *Evolving and increasingly hazardous radiation levels in space. (top) ACE dose rates (red) are based on fits to CRIS spectra; CRaTER measurements (green) from the zenith-facing D1/D2 detectors are used as proxies for lens dose rates behind 0.3 g/cm2 Al shielding. The*

sunspot number predictions (the lower black and blue dashed lines) show two cases based on a Gleissberg-like and a Dalton-like minimum, the results of which are similar. The dose predictions (solid blue line and the upper black and blue dashed lines) are from a sunspot-based model of the heliospheric magnetic field and the correlated variation in modulation of GCRs. The ACE data, CRaTER data, and model results are projected to the lunar surface. (bottom) Same as top panel but for a longer time span.

Relevant Publications

- Goelzer, M. L., Smith, C. W., Schwadron, N. A., and McCracken, K. G., An analysis of heliospheric magnetic field flux based on sunspot number from 1749 to today and prediction for the coming solar minimum, Journal of Geophysical Research (Space Physics), 118, 7525, 2013
- Schwadron, N. A., Smith, S., and Spence, H. E., The CRaTER Special Issue of Space Weather: Building the observational foundation to deduce biological effects of space radiation, Space Weather, 11, 47, 2013
- McComas, D. J., Angold, N., Elliott, H. A., Livadiotis, G., Schwadron, N. A., Skoug, R. M., and Smith, C. W., Weakest Solar Wind of the Space Age and the Current "Mini" Solar Maximum, The Astrophysical Journal, 779, 2, 2013
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- Schwadron, N. A., Blake, J. B., Case, A. W., Joyce, C. J., Kasper, J., Mazur, J., Petro, N., Quinn, M., Porter, J. A., Smith, C. W., Smith, S., Spence, H. E., Townsend, L. W., Turner, R., Wilson, J. K., and Zeitlin, C., Does the worsening galactic cosmic radiation environment observed by CRaTER preclude future manned deep space exploration?, Space Weather, 12, 622, 2014a
- Smith, C. W., McCracken, K. G., Schwadron, N. A., and Goelzer, M. L., The heliospheric magnetic flux, solar wind proton flux, and cosmic ray intensity during the coming solar minimum, Space Weather, 12, 499, 2014
- Schwadron, N. A., Goelzer, M. L., Smith, C. W., Kasper, J. C., Korreck, K., Leamon, R. J., Lepri, S. T., Maruca, B. A., McComas, D., and Steven, M. L., Coronal electron temperature in the protracted solar minimum, the cycle 24 mini maximum, and over centuries, Journal of Geophysical Research (Space Physics), 119, 1486, 2014b

Relevant Presentations

- Schwadron, N. A., Earth Moon Mars Radiation Environment Module, LWS Workshop, Princeton, NJ, Sept 18-20, 2013
- Schwadron, N., Spence, H., and Wilson, J., Lunar radiation environment, 40th COSPAR Scientific Assembly. Held 2-10 August 2014, in Moscow, Russia, Abstract B0.1-4-14., 40, 2014
- Schwadron, N. A. , Implications of the Worsening GCR Radiation Environment, Space Radiation Environment, Space Weather Week, Boulder CO, April, 2014
- Schwadron, N. A., Implications of the Worsening Space Radiation Panelist International Space Medicine Summit, July, 2014
- Schwadron, N. A., Lunar Radiation Environment, B0.1-0004-14, COSPAR, Moscow, July, 2014
- Schwadron, N. A., Panelist on Radiation Effects, International Space Medicine Summit, Rice, Houston, TX June, 2014
- Schwadron, N. A., Increasing Biological Hazards from Solar Energetic Particles and Cosmic Rays, Space Weather Workshop, Boulder, CO, April 7-11, 2014
- Isenberg, P. A., Ion kinetics in the solar wind generation region, Living With a Star Science Meeting, Portland, OR, November, 2014.

II.2 C-SWEPA Progress in Modeling Solar Energetic particles

Solar energetic particles (SEPs) present significant acute hazards to human and robotic missions. The C-SWEPA project provides a unique coupling between MHD models and the energetic particle models, allowing fundamental capabilities to now-cast and predict the SEP events.

Significant progress has been made with PREDICCS (Predictions of Radiation from REleASE, EMMREM, and Data Incorporating the CRaTER, COSTEP and other SEP measurements, http://prediccs.sr.unh.edu), which is an online system that utilizes data from various satellites in conjunction with numerical models (C-SWEPA) to produce a near-real-time characterization of the radiation environment of the inner heliosphere. PREDICCS offers the community a valuable tool in forecasting events and improving risk assessment models for future space missions, providing up to date predictions for dose rate, dose equivalent rates and particle flux data at Earth, Moon and Mars. Joyce et al. [2013b] presented a comparison between lunar dose rates and accumulated doses predicted by the PREDICCS system with those measured by the Cosmic Ray Telescope for the Effects of Radiation (CRaTER) instrument aboard the Lunar Reconnaissance Orbiter (LRO) spacecraft during three major solar events in 2012 (Figure 5). We also plot the dose rate measured by the microdosimeter aboard LRO for comparison, as well as additional PREDICCS dose rates for different levels of shielding, which demonstrate how advanced knowledge of events may be used to reduce radiation exposure to astronauts. Joyce et al. [2013b] find that the dose rates and accumulated doses predicted by PREDICCS and measured by CRaTER during the three solar events are in good agreement and differ by at most 40 percent. From this, we conclude that PREDICCS offers a credible characterization of the lunar radiation environment. The Joyce et al. [2013b] study offers the first long-term validation of C-SWEPA radiation models using in-situ measurements and demonstrates how valuable PREDICCS should become in future efforts in risk assessment and in the study of radiation in the inner heliosphere.

This study also demonstrates typical dose rates and accumulated doses associated with large solar events.

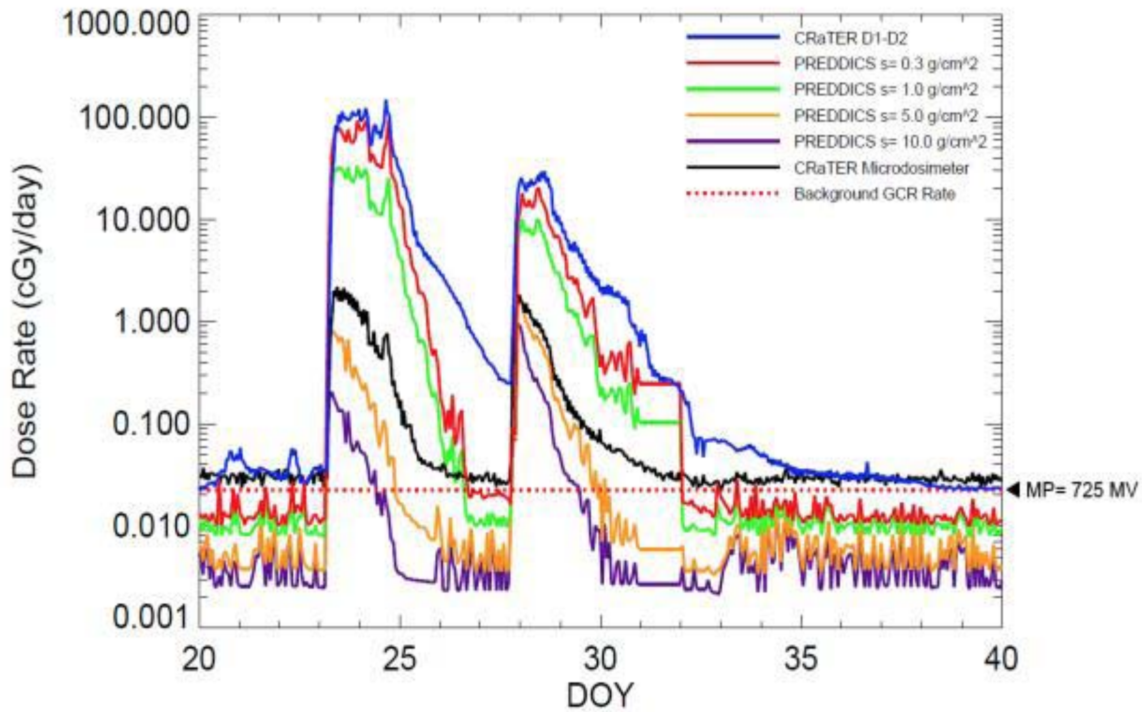

Figure 4. *Dose rates measured by CRaTER (blue) vs. those predicted by PREDICCS for various levels of shielding during the January 2012 solar event. The 0.3 g/cm2 shielded PREDICCS dose rate (red) offers the closest comparison to the level of shielding seen by CRaTER. Figure taken from Joyce et al., [2013b].*

Kozarev et al. (2013) coupled results from a detailed global three-dimensional MHD time-dependent CME simulation to a global proton acceleration and transport model, in order to study time-dependent effects of SEP acceleration between 1.8 and 8 solar radii in the 2005 May 13 CME. Kozarev et al. (2013) find that the source population is accelerated to at least 100 MeV, with distributions enhanced up to six orders of magnitude. Acceleration efficiency varies strongly along field lines probing different regions of the dynamically evolving CME, whose dynamics is influenced by the large-scale coronal magnetic field structure. We observe strong acceleration in sheath regions immediately behind the shock. Results from the Kozarev et al. (2013) study are shown in Figures 5-7.

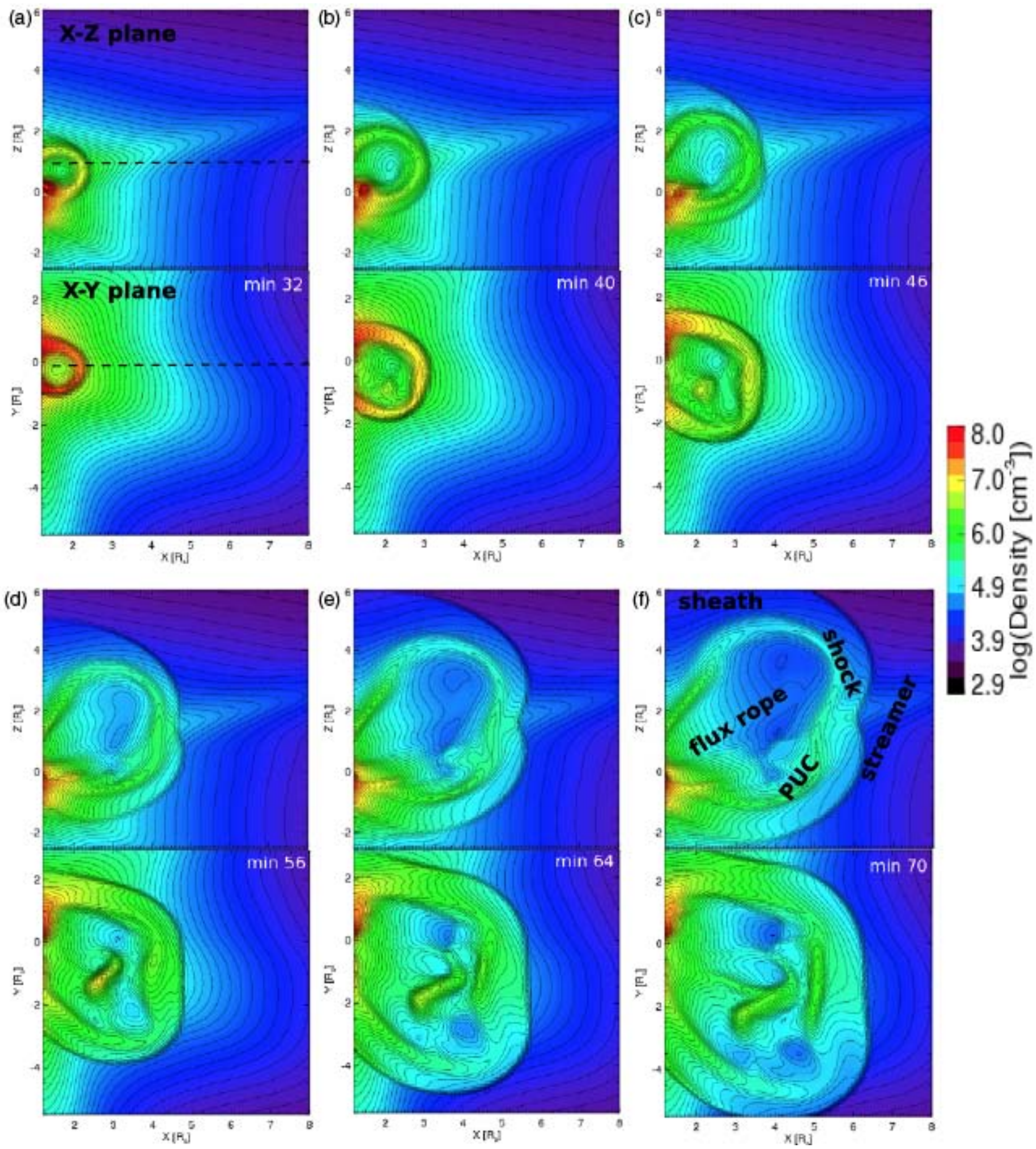

Figure 5. *X–Z and X–Y slices showing color and line contours of proton density for six snapshots of the CME simulation used in Kozarev et al. [2013]. The snapshots span about 38 minutes of simulation time. The larger structure is a coronal streamer.*

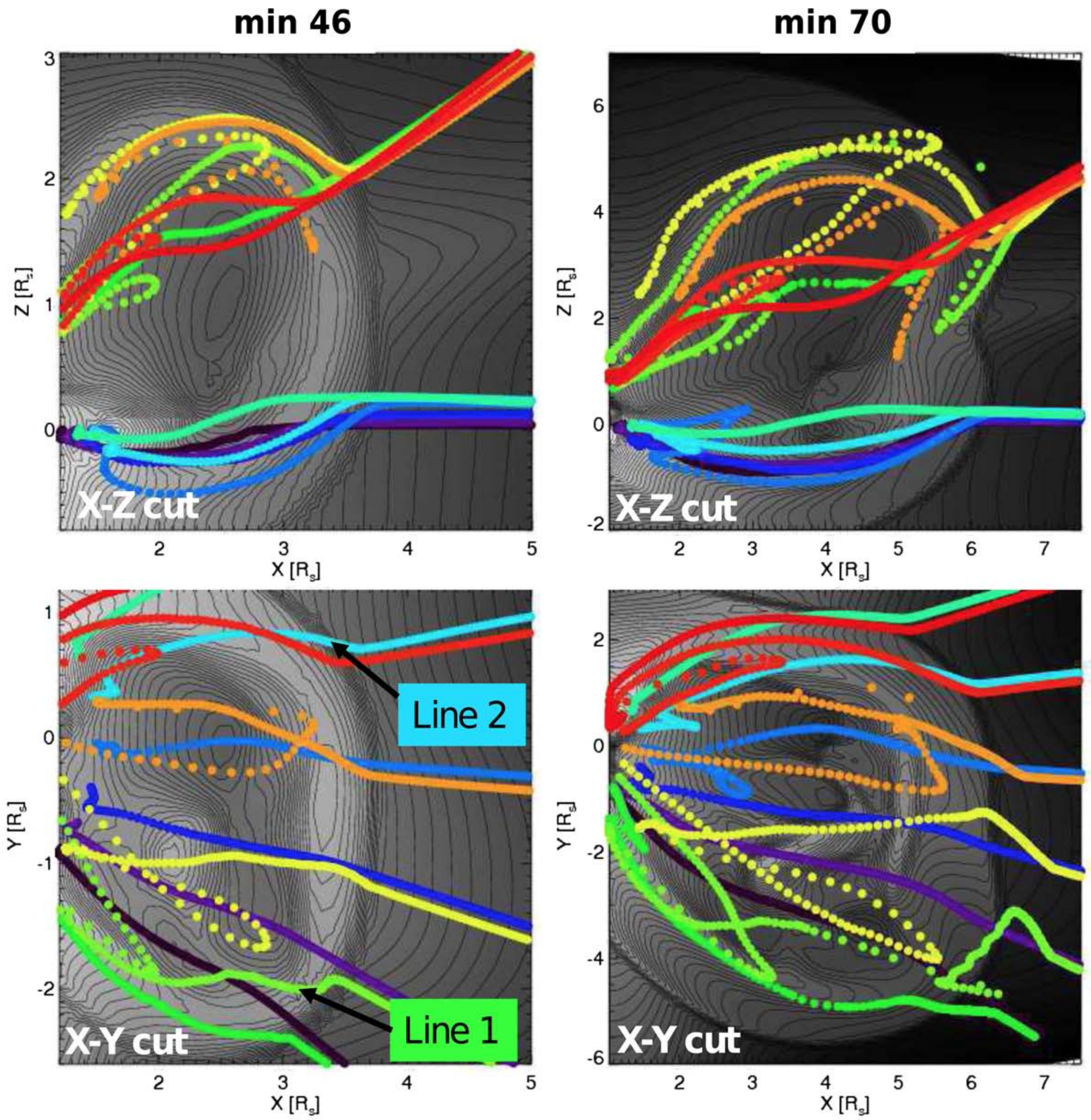

Figure 6. *Evolving CME distorts the C-SWEPA grid lines, as can be seen in these panels. The solar wind density is shown as grayscale density contours. Overlaid, color dots represent the grid node positions along individual field lines. The top and bottom panels show the X–Z and X–Y cuts for two times, similar to previous figures. The two lines marked "Line 1" and "Line 2" point to the two lines discussed later in this section. Figure taken from Kozarev et al., 2013.*

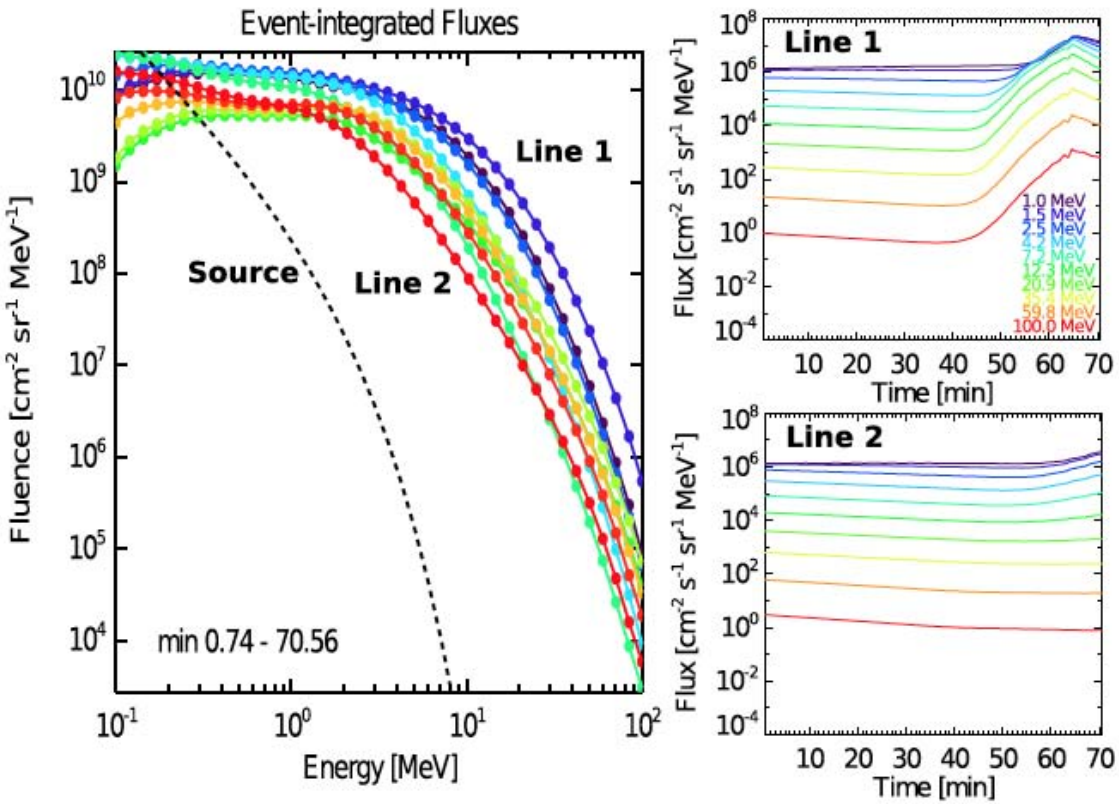

Figure 7. *Panel (a): event-integrated fluences for the 10 lines shown in Figure 5. Proton energy is on the X-axis; fluence is on the Y-axis. The dashed line represents the fluence at the model inner boundary (source). Panels (b) and (c): simulated flux, "measured" over time at a constant distance of ~8 RS on the two lines denoted in the bottom left panel of Figure 5 as Line 1 and Line 2, respectively. Time is on the X-axis; proton flux is on the Y-axis. Figure taken from Kozarev et al. [2013].*

The C-SWEPA team has (1) completed an analysis of the July 23, 2012 extreme CME event, including the acceleration of energetic particles; (2) completed a thermodynamic MHD relaxation run for the Bastille Day event; and (3) began preliminary simulations with an embedded spheromak field within our cone-model generator.

A suite of model solutions for the July 23, 2012 CME explored a variety of input parameters, including the shape, duration, amplitude, and speed of the main CME as well as whether or not a precursor CME was first launched. One promising candidate was chosen to provide the background plasma and magnetic field parameters to accelerate protons using the C-SWEPA code. The results suggest that the included particle acceleration mechanisms can more than adequately produce distributions like those observed.

A thermodynamic MHD relaxation run was completed of the Bastille Day event corona with improved spatial resolution and inserted a pre-relaxed flux rope into the solution. The test, which was successful, was to assess whether the rope would remain coherent or transform into a sheared arcade. While a significant amount of magnetic energy was still released as the system adjusted to the inserted, strong-field flux rope, the rope now retains its coherence much better. Moreover, the improved resolution greatly improves the quality of synthetic satellite images in the sense that spurious oscillations and disturbances that we had previously seen in the images are now almost completely absent within the active region.

The C-SWEPA team further developed an analytic description of the modified Titov-Demoullin (TDm) model. We were able to eliminate the current concentrations surrounding the symmetry axis of the TDm current ring, allowing us to study tilted (with respect to the vertical direction) flux rope configurations without introducing unphysical currents into the domain. We are currently running test simulations of this updated version.

To address the limitation that current cone model simulations cannot capture any of the magnetic structure within ICMEs, we developed a simple prescription of a spheromak magnetic field that can be inserted within a cone model ejecta. Although the dynamics of the eruption are still primarily controlled by the plasma properties of the ejecta (speed and density primarily), initial tests suggest that even a modest magnetic field modifies the profiles of the disturbance at 1 AU. We are in the process of investigating these results in more detail, and, in particular, assessng the effects of different field strengths within the ejecta.

Figures 8 – 14 exemplify results of recent model runs that explore the effects of CMEs on solar energetic particles. These results have been incorporated in one published paper [Schwadron et al., 2014c] and in three draft manuscripts in preparation.

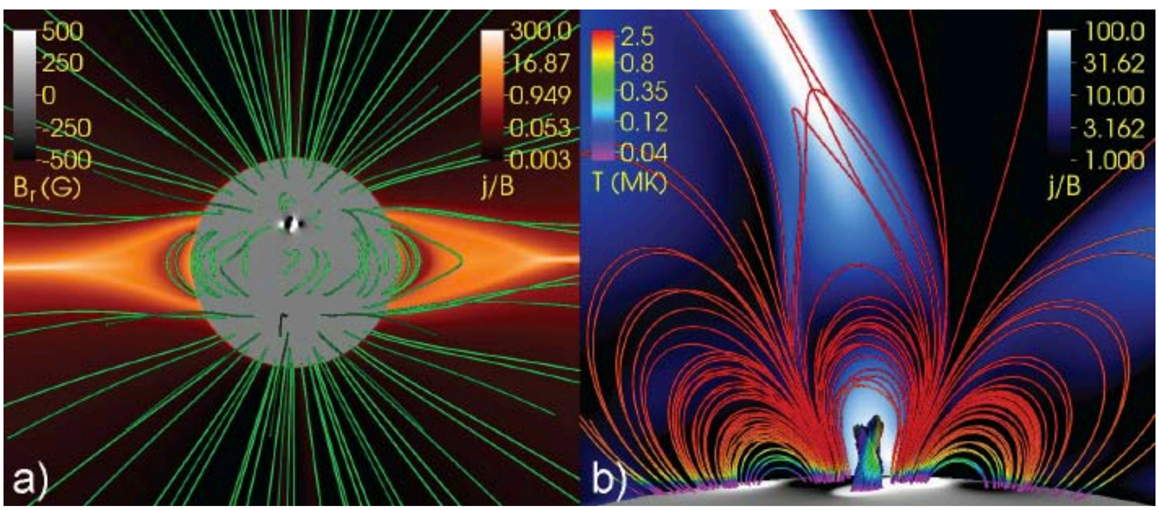

Figure 8. *[Titov et al., 2013] Magnetic field configuration after flux rope insertion and subsequent relaxation. active region located in the northern hemisphere. b): View on the active region. Field lines are colored by temperature. Cold (and dense) flux rope core is visible in the center. The streamer is seen overlying the active region.*

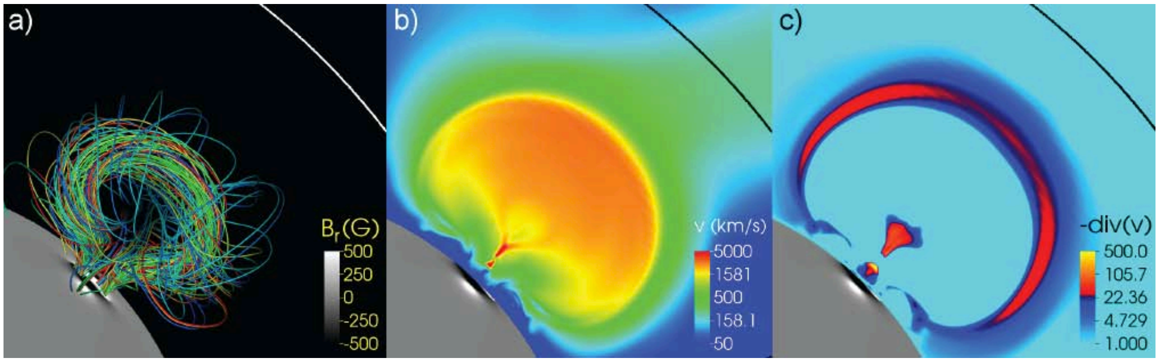

Figure 9. *Modified version of the flux rope model by Titov & Demoulin (1999) above the central polarity inversion line of an active region. Active region and flux rope total unsigned flux of 7.5 x 10^{22} Mx. Maximum radial-field strength of 1070 G at the photospheric level. [from Gorby et al., 2013]*

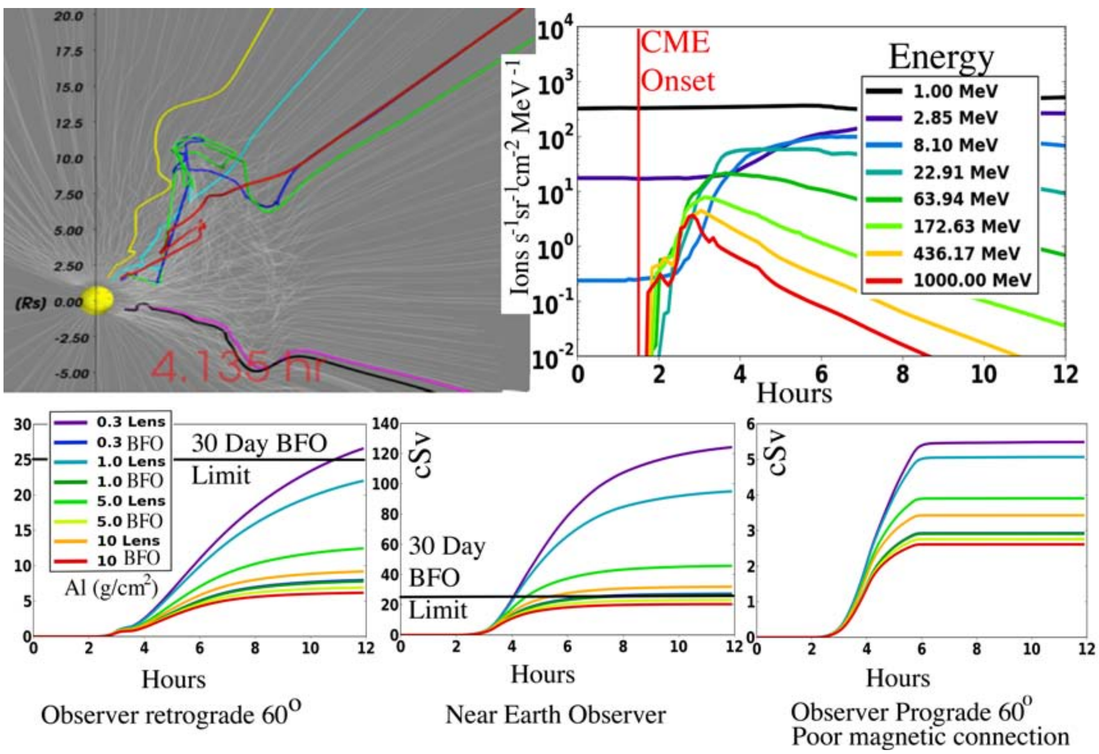

Figure 10. *Energetic particles are accelerated over a broad latitudinal and longitudinal spread from the CME released following destabilization shown in Figure 10. The colored magnetic field lines show strong distortions by the plasma flow. [from Schwadron et al., 2014c]*

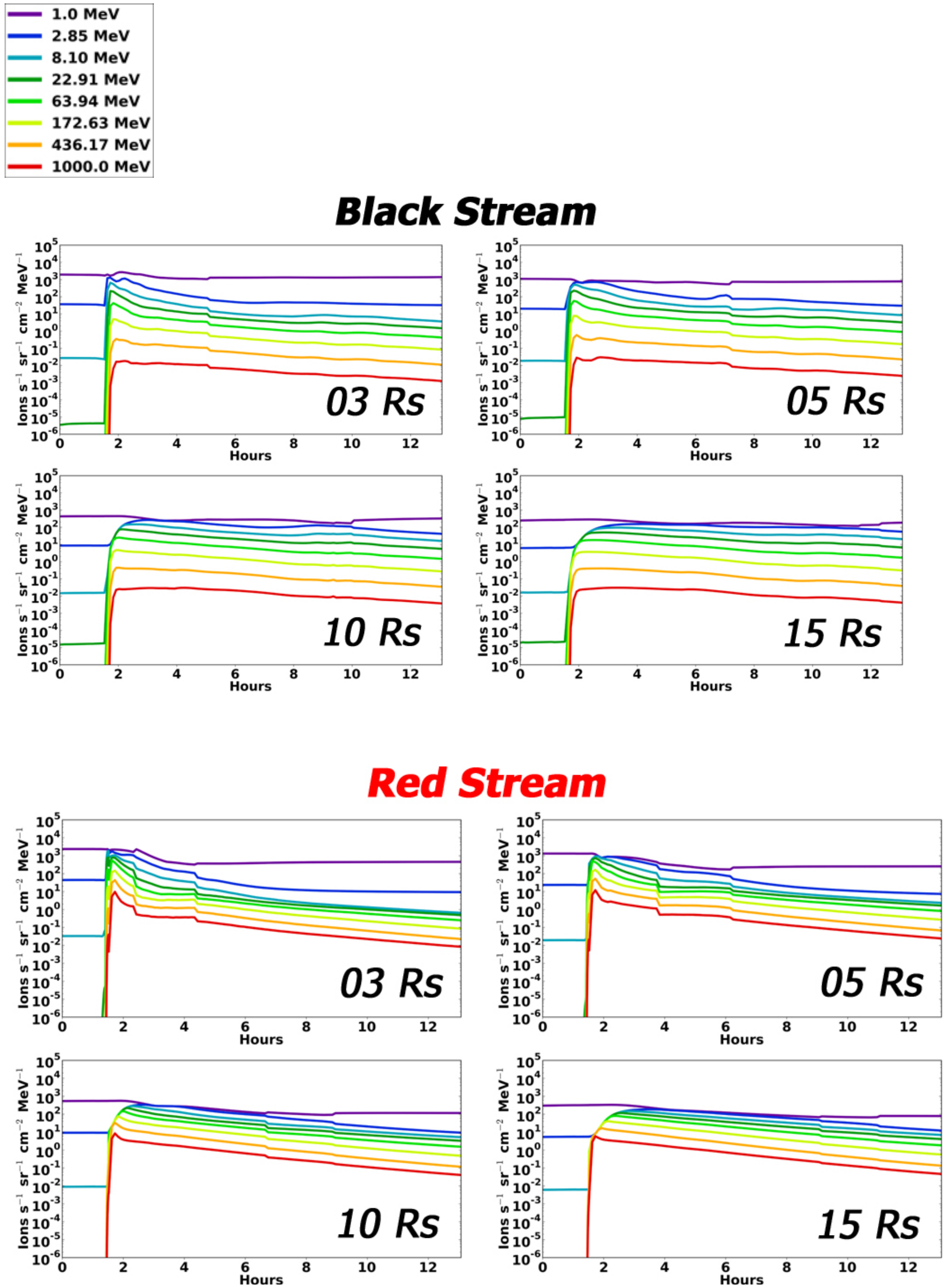

Figure 11. *The CME from figures 10 and 11 causes particle acceleration up to GeV energies. Shown here are the time-dependent histories of energetic particles at 3, 5, 10 and 15 solar radii along the Black and Red Streamlines shown in Figure 11. [from Gorby et al., 2013]*

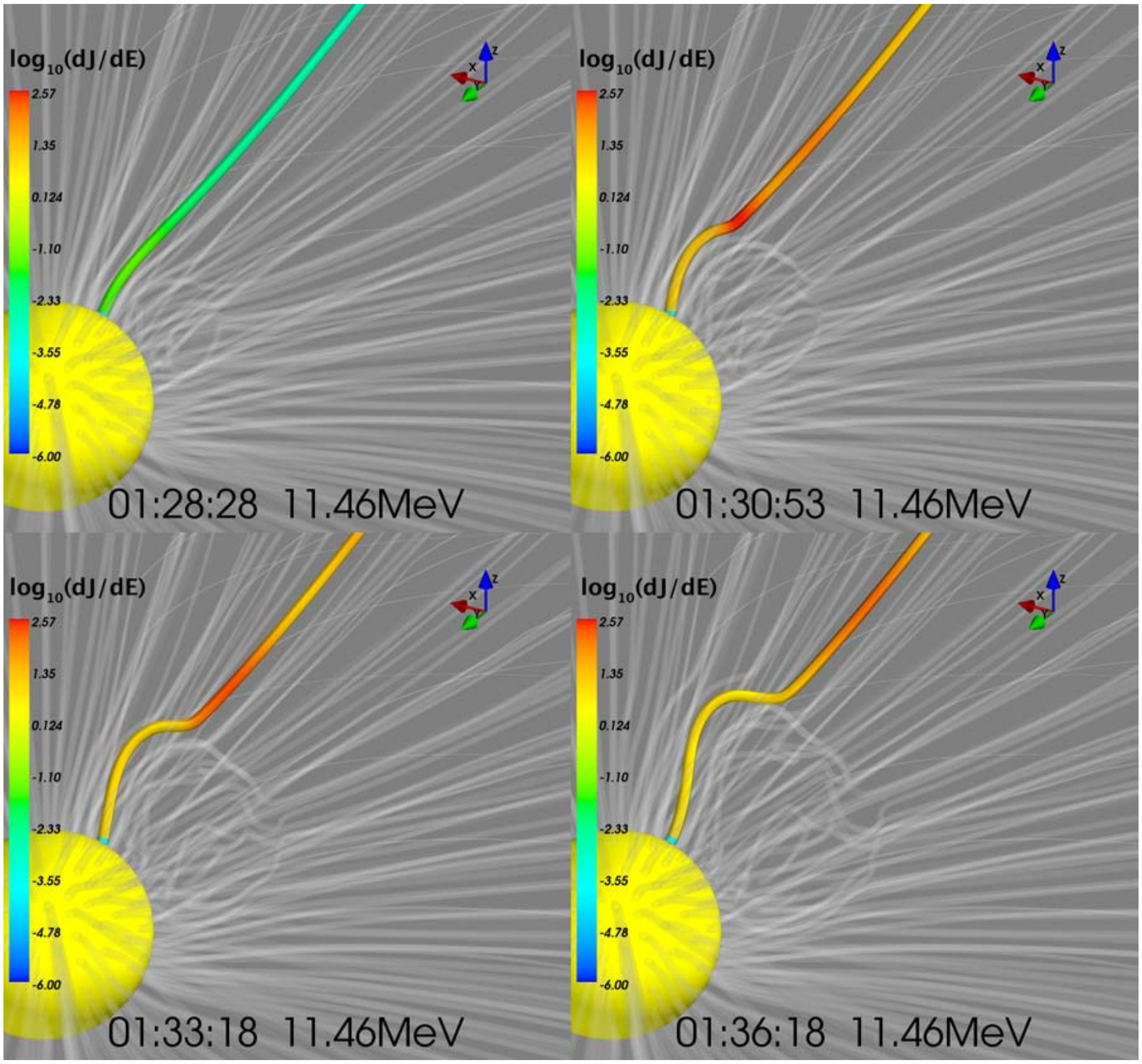

Figure 12. *Domain with the stream associated with the plots on the left colored by log10 of the differential energy flux at 11.46 MeV. [From Gorby 2014]*

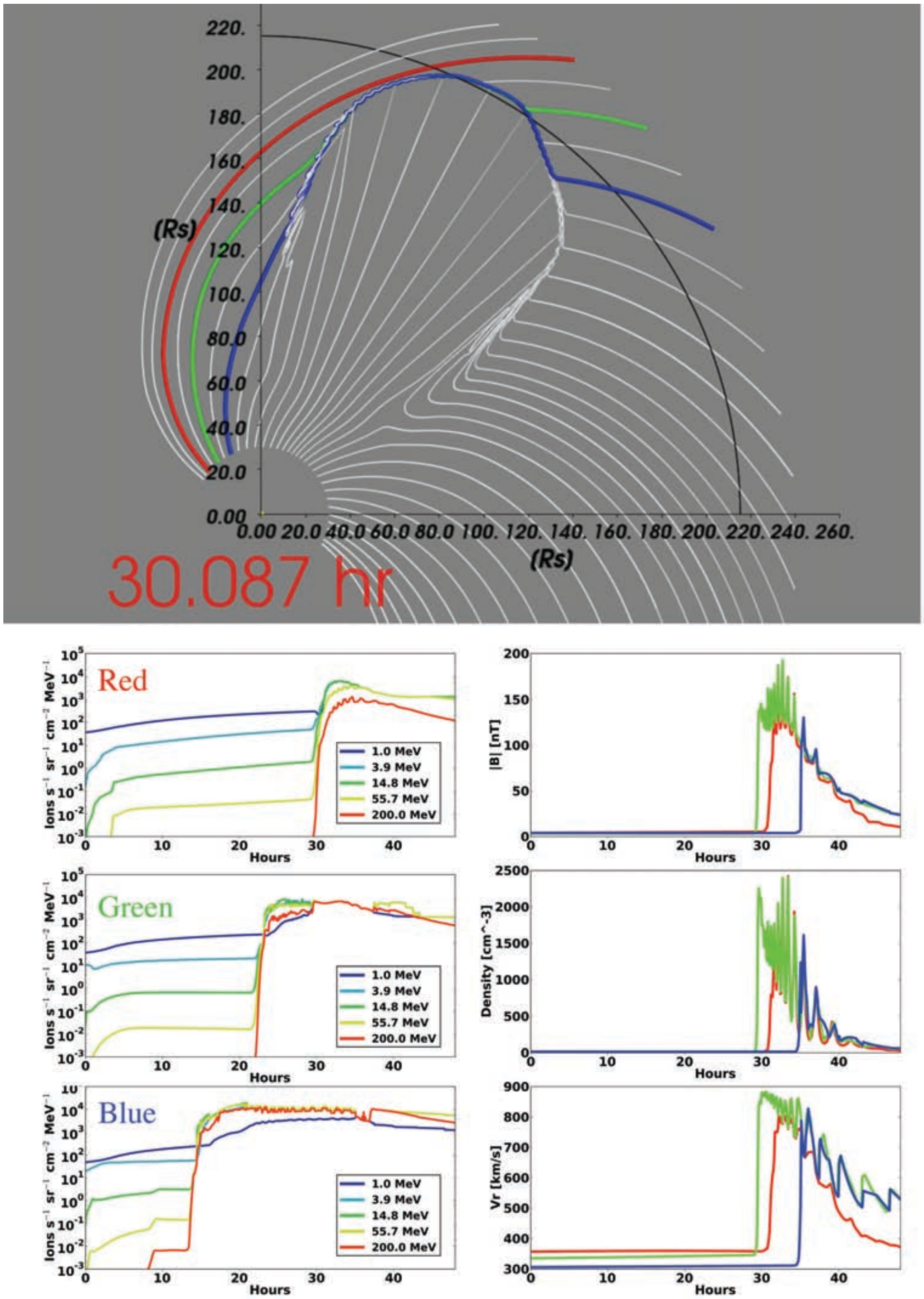

Figure 13. *C-SWEPA models solve for the energetic charged particle distributions along and across magnetic field lines, from Kev to Gev energies. The code produces time histories of the particle distribution functions at various pitch angles, energies, and locations within the heliosphere. The red/green/blue traces shown here represent fluxes associated with the west/center/east of the ICME, that is, two at the flanks and one near the nose. [From Riley et al., 2013]*

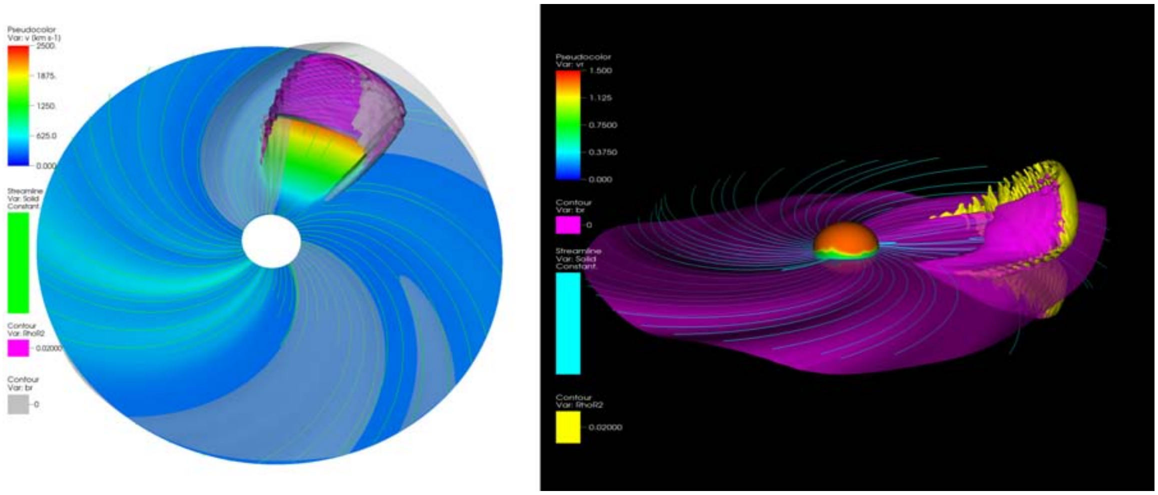

Figure 14. *Two 3-D views of ICME (simulation 15) as it approaches 1 AU. The legends to the left of each panel indicate what parameters are being displayed. A selection of interplanetary magnetic field lines are also shown [From Riley et al., 2013].*

Schwadron et al. (2014a) also examined the probabilities of SEP events in the cycle 24 maximum. Because of the weak activity, the probability of large SEP events was greatly diminished. Again, this has major implications for human exploration. Specifically, this suggests that solar maximum may be a good time to send humans into deep space provided that solar activity remains suppressed in coming maxima.

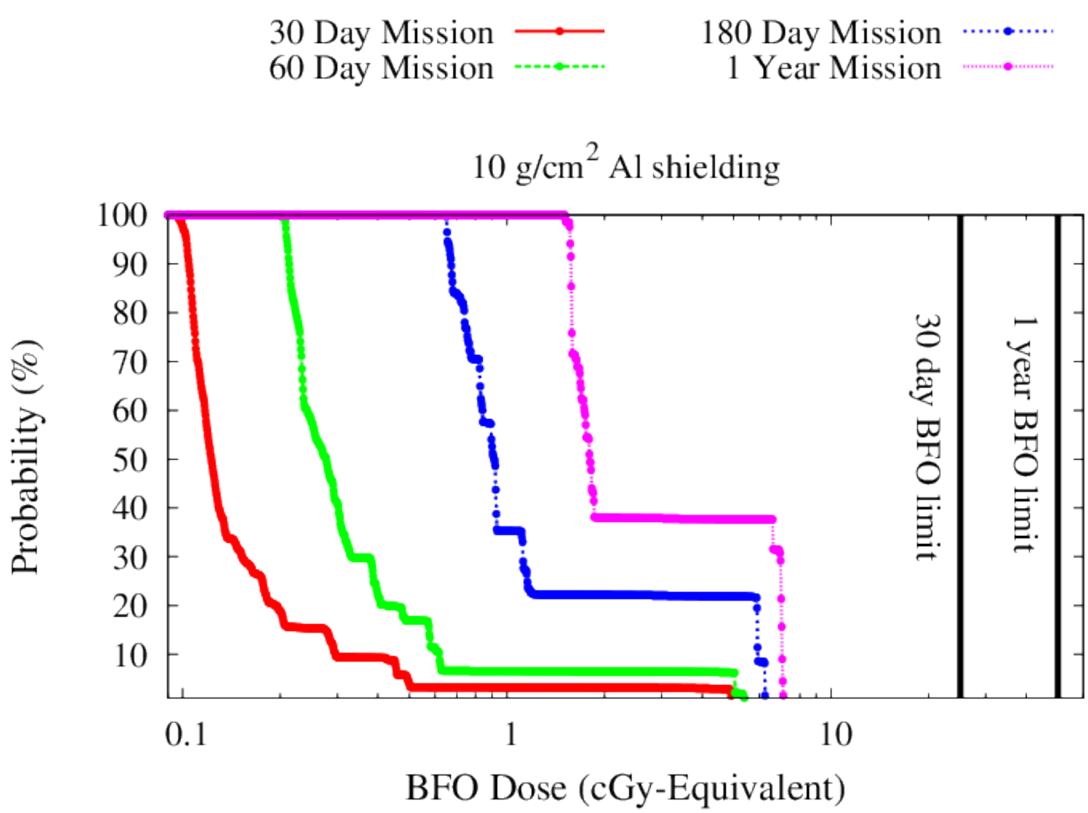

Figure 15. *Probability (%) versus integrated BFO dose for 30 day to 1 year missions. We use the PREDICCS database (http://prediccs.sr.unh.edu) to build up statistics for the probability of SEP events of varying integrated dose behind spacecraft shielding (10 g/cm^2). The database currently provides doses for the period from July 2011 through April 2014. The PREDICCS doses are derived from proton spectra and use dose in 10 g/cm^2 water as a proxy for the blood forming organ (BFO) dose.*

Relevant Publications:

- Valori et al., "Initiation of Coronal Mass Ejections by Sunspot Rotation", Proceedings IAU Symposium No. 300, 2013.
- Torok et al., "The Evolution of Writhe in Kink-Unstable Flux Ropes and Erupting Filaments", submitted to PPCF (Plasma Physics and Controlled Fusion).
- Torok et al., "Distribution of Electric Currents in Solar Active Regions", submitted to ApJ Letters
- Lionello et al., "Magnetohydrodynamic Simulations of Interplanetary Coronal Mass Ejections", ApJ 777, 76 (2013).
- Leake et al., "Simulations of Emerging Magnetic Flux. I: The Formation of Stable Coronal Flux Ropes", ApJ 778, 99 (2013).
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- Jon Linker presented a seminar at the Observatoire de Paris in Meudon entitled "Modeling CMEs: Eventual Space Weather Applications?" on 9/25. The seminar described our approaches to modeling CME events, with examples from an idealized extreme event and initial results from simulations of the Bastille Day event. The talk also described the coupling of MAS CME simulations to EPREM solutions of the focused transport equation, and showed the resulting generation of high intensity SEPs in the idealized extreme event simulations.
- Jon Linker and Tibor Torok attended the FESD/C-SWEPA team meeting at the University of New Hampshire October 15-16, and presented talks describing the field line evolution and associated MHD quantities in the idealized CME simulation. Discussions led to a recognition that we need to unambiguously identify which features of the MHD solution are producing the SEP acceleration.
- Jon Linker presented a colloquium at the University of Sydney Department of Physics on 10/27 in which he described the use of the new TDm flux rope model in simulations of the Bastille Day event.
- Slava Titov presented the invited talk "Global Magnetic Topology and Large-Scale Dynamics of the Solar Corona" in session E2.1, Coronal Magnetism, at the COSPAR meeting in Moscow, August 3-9
- Titov, V., Torok, T., Mikic, Z., and Linker, J. A., A Method for Embedding Circular Force-Free Flux Ropes in Potential Magnetic Fields, American Astronomical Society Meeting Abstracts #224, 224, #212.04, 2014

II.3 Survey of Spectral Properties of SEP events from solar cycles 23 and 24

Members of the C-SWEPA team have identified all SEP events observed at ACE and Wind during solar cycles 23 and 24. We have obtained the energy spectra of ~0.1–100 MeV/nucleon heavy ions for 11 species H, He, C, N, O, Ne, Mg, Si, S, Ca, and Fe during each of these events using ACE/ULEIS and ACE/SIS data. We have also performed spectral fits to these data to calculate the break-point energies or the energy at which each species rolls-over (departs from a single power-law). An example of these types of energy spectral breaks during an ESP event and how they are related to existing theoretical ideas is shown in Figure 15.

Recent particle acceleration models have taken account of the complex interplay between the injection of compound suprathermal seed populations and the time-dependent evolution and spatial curvature of IP shocks (e.g., Tylka & Lee 2006; Li et al., 2009). To date such models have simulated the time-histories of a variety of heavy ion species during individual SEP events (e.g., Ng et al., 2003; Li et al., 2005) and constructed event-integrated or event-averaged heavy ion spectra over a broad energy range that were then compared with SEP observations near Earth (e.g., Mewaldt et al., 2007; Mason et al., 2013).

For instance, Tylka & Lee (2006) neglected transport effects and used an analytical approach to model the event-integrated abundances of heavy ions and the energy-dependence of Fe/O in two large SEP events. They assumed that the heavy ion differential intensity spectra in individual SEP events can be fitted with power-laws modulated by exponential roll-overs of the form $J_X(E,\theta_{Bn}) = C_X E^{-\gamma} \exp(-E/E_{0X})$, where J_X is the differential intensity of species X at energy

E measured in MeV/nucleon, C_X is the normalization constant, γ is the power-law index, and E_{0X} is the e-folding energy, i.e., the energy at which the spectrum starts to roll-over or deviate from a pure power-law (e.g., Jones & Ellison 1991). In this model, the behavior of the heavy ion abundances and the energy-dependence of Fe/O arise from the relative amount of solar wind-like or flare-like material in the suprathermal seed population; the dominant material being determined by the shock's θ_{Bn} or the injection threshold. In the Tylka & Lee model, these factors result in producing roll-overs or breaks in the event-integrated heavy ion spectra that depend on the ion's Q/M ratio and the shock's θ_{Bn} as follows: $E_{0X} / E_{0H} \equiv (Q_X / M_X)^{\delta} (\sec\theta_{Bn})^{2/(2\gamma-1)}$. Here E_{0H} is the proton roll-over energy, the exponent δ arises from the Q/M-dependence of the parallel mean free path $\lambda_{//} \propto (Mv/Q)^s$ and is given by $\delta = 2s/(s+1)$ when the parallel diffusion coefficients $\kappa_{//}$ for different species are equal (see e.g., Cohen et al., 2005; Li et al., 2009). For simplicity, Tylka & Lee (2006) assumed that δ~1, i.e., s~1 and found good agreement between the event-integrated abundances of heavy ions and the energy-dependence of Fe/O in two large SEP events.

Li et al. (2009) took account of transport effects and used the equal diffusion coefficient condition to obtain a more general model in which δ has values ranging from ~0.2 for perpendicular shocks to ~2 for parallel shocks, with values in between corresponding to oblique shocks. In this model, the strongest Q/M-dependence in the spectral roll-overs occur at parallel shocks, while the weakest occurs at perpendicular shocks. Note that Mewaldt et al. (2007) obtained a value of δ ~1.75 for the October 2003 ESP/SEP event.

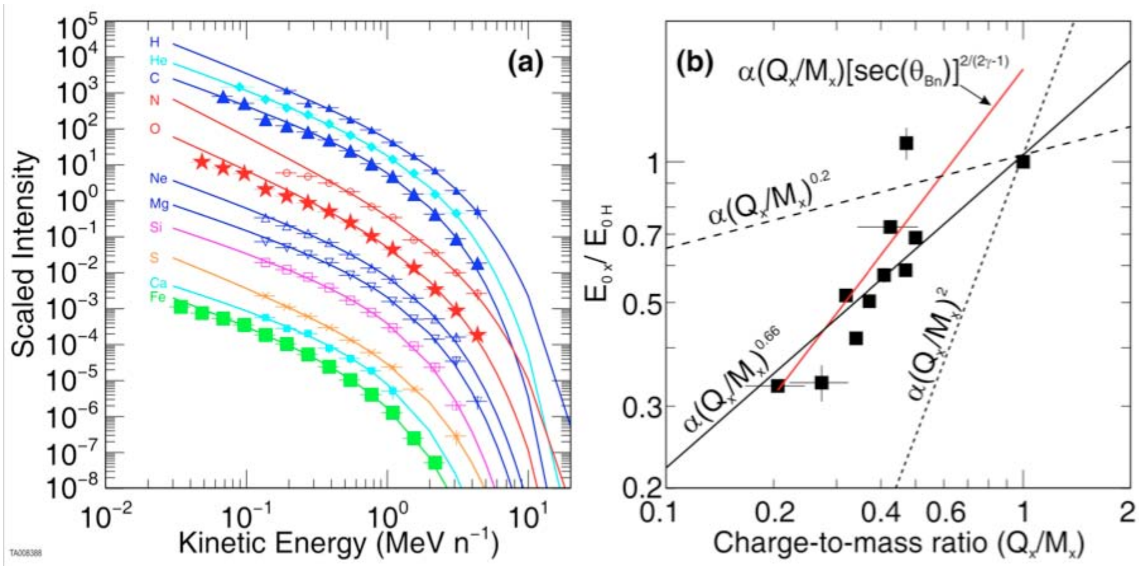


Figure 16: *(a) Heavy ion spectra and fits (see text for details) for the IP shock-associated ESP event on June 26, 1999. (b) Scatterplots of e-folding energies E_{0X}/E_{0H} for species X vs. the ion's Q/M ratio. The dashed and dotted black lines represent* $E_{0X}/E_{0H} \propto (Q_X/M_X)^{\delta}$ *for δ=0.2 and δ=2, corresponding to perpendicular and parallel shocks (after Li et al., 2009). Red line: Fits to* $E_{0X}/E_{0H} \equiv (Q_X/M_X)(\sec\theta_{Bn})^{2/(2\gamma-1)}$ *assuming a constant γ=1.45 for all species (after Tylka & Lee 2006); black line: least squares fit of the form* $E_{0X}/E_{0H} \propto (Q_X/M_X)^{0.66}$. *The black line is a reasonable representation of the Q/M-dependence for this event, in agreement with the Li et al. (2009) simulations for an oblique IP shock.*

Figure 16 shows a preliminary analysis for an IP shock event from the Desai et al. (2003; 2004) surveys, which had θ_{Bn}≈55°±2° and also exhibited a strong energy dependence in the Fe/O ratio. The H-Fe differential intensity spectra in Figure 15a are fitted by the Jones & Ellison expression, with free parameters C_X , γ_X, and E_{0X}. Figure 15b shows the ratio of roll-over or e-folding energies E_{0X}/E_{0H} vs. the Q/M ratio of each species *X*. The solid black line shows a fit to the data with $E_{0X}/E_{0H} \propto (Q_X/M_X)^{\delta}$ with δ~0.67±0.08; dashed black lines show the Q/M-dependence with δ~0.2 and δ~2. The red line shows a fit of the form $E_{0X}/E_{0H} \equiv (Q_X/M_X)(\sec\theta_{Bn})^{2/(2\gamma-1)}$ assuming a constant *γ~1.45* for all species (after Tylka & Lee 2006). Figure 15b shows that the red line with δ~1 and the solid black line with δ~0.66 are reasonable representations of the observed Q/M-dependence of the spectral roll-overs, and are therefore in apparent agreement with model expectations of injection and acceleration of solar-wind like material at an oblique shock.

Relevant Publications:

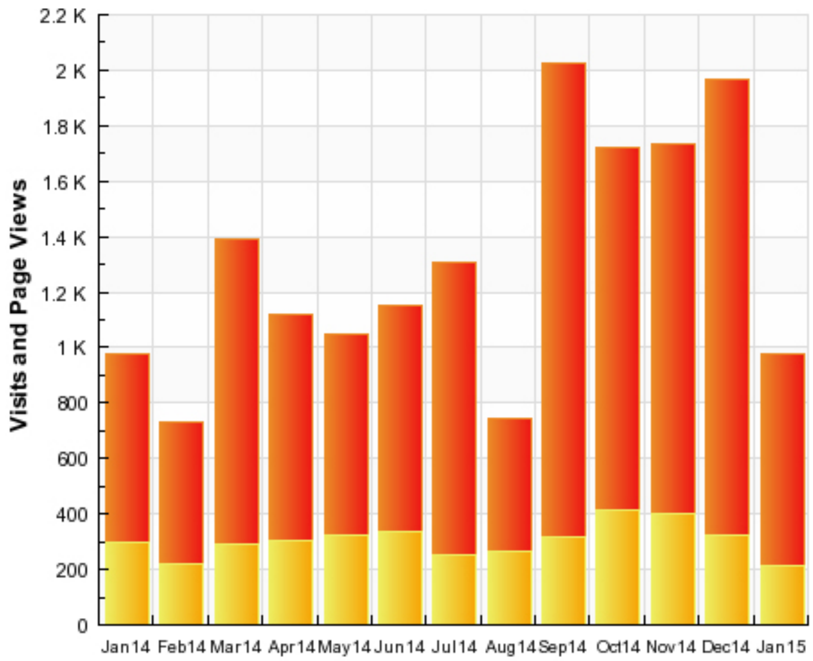
- Mason, G. M., M. I. Desai, R. A. Mewaldt, and C. M. S. Cohen, "Particle Acceleration in the Heliosphere," in American Institute of Physics Conference Proceedings, vol., 1516, pp 117-120, 2013

Relevant Presentations

- Desai, M. I., D. J. McComas, E. R. Christian, A. C. Cummings, J. Giacalone, M. E. Hill, S. M. Krimigis, S. A. Livi, R. L. McNutt, R. A. Mewaldt, D. G. Mitchell, W. H. Matthaeus, E. C. Roelof, T. T. von Rosenvinge, N. A. Schwadron, E. C. Stone, M. M. Velli, and M. E. Wiedenbeck, "Suprathermal and Solar Energetic Particles: Key Questions for Solar Probe Plus," Invited Talk (30 minutes), presented at the 1st Solar Probe Plus Workshop, Pasadena, March 26-29, 2013

II.4 Data Sharing and Products

The database of Wind IP shocks and Rankine solutions contributed by Mike Stevens (SAO/CfA) is alive and well, and up to date through July of this year at http://www.cfa.harvard.edu/shocks/wi_data/. The data set is an extremely valuable resource for the heliopshysics community since it quantifies the strength, frequency and detailed behavior of interplanetary shocks. Modeling using the C-SWEPA framework is now being extended to 1 AU and comparison with the IP shock dataset is increasingly valuable as a means of validating simulation results. Figure 17 shows the number of page views and visits to the online shock database for each month over the 2014. Over the last six months there have been about 2,000 shocks viewed each month! This indicates that the database is heavily utilized and a vital contribution to C-SWEPA.



Month of the Year	Visits	Page Views
Jan15	213	977
Dec14	326	1,967
Nov14	402	1,737
Oct14	413	1,722
Sep14	318	2,024
Aug14	266	742
Jul14	255	1,305
Jun14	339	1,152
May14	325	1,049
Apr14	304	1,121
Mar14	292	1,392
Feb14	218	734
Jan14	296	979

Figure 17. *Number of page views and visits to the online shock database for each month over the last year. Over the last six months there have been about 2,000 shocks viewed each month.*

NASA's Virtual Energetic Particle Observatory (VEPO) provides enhanced access to energetic particle data sets of strong interest to C-SWEPA for comparison of time intensities and variously-averaged flux spectra from still-operational experiments on ACE, Stereo-A/B, Wind, SOHO, and GOES. Archival data are also available from Ulysses, IMP-8, Pioneer 10 & 11, and Voyager 1 &2. Fluxes and spectra can be compared from various sources for omnidirectional protons, helium, and heavier ions. The most recent addition includes directional sectored fluxes and spectra. VEPO enables C-SWEPA and other users to see selected fluxes and spectra averaged over user-selected time intervals. VEPO is very useful for comparison of evolving flux spectra from solar energetic particle (SEP) events as observed by multiple spacecraft sources in the heliosphere. A key motivation of these VEPO services is to enable cross-comparison of spectra from different sensors on the same spacecraft and from different locations to check flux calibrations. This function becomes maximally useful in the case of inner heliospheric "reservoir events" in which spatial gradients vanish during the decay phases of some SEP events. VEPO is now planning to add such services for energetic electron data products.

NASA funding for VEPO is continuing through FY14 and may continue at levels TBD into the future. C-SWEPA Collaborator John Cooper at NASA Goddard Space Flight Center is the Principal Investigator for VEPO. The web site is accessible at vepo.gsfc.nasa.gov.

The VEPO team have added additional capabilities for energetic particle scatter plots and spectrograms. The VEPO team has begun to expand the COHOWeb service to Voyager and other heliospheric spacecraft to allow correlations of magnetic field, plasma, and energetic particle data. See http://omniweb.gsfc.nasa.gov/ftpbrowser/flux_spectr_m.html and http://omniweb.gsfc.nasa.gov/coho/for latest versions.

John Cooper (C-SWEPA CoI) will be talking at the APS-DPS meeting at Baltimore in April about applications of these VEPO services to heliospheric data surveys, e.g. for identification of SEP reservoir events. VEPO is also a testing platform to improve its SPDF flagship services, e.g. CDAWeb and OMNIWeb.

Relevant Presentations

- James, A., M. Stevens, K. Korreck, The Heating of Helium Across Interplanetary Shocks in Front of Coronal Mass Ejections, AAS, 2014 (Drew from shock database)
- Korreck, K., M. Stevens, S. Lepri, J. Kasper, Heavy Ion Heating at Shocks in the Heliosphere, Fall AGU, 2014 (Drew from shock database)
- Mike Stevens gave a colloquium at MIT's Plasma Science and Fusion Center IAP "Space Weather Research: Scientific and Social Issues of Living Near a Star" on Jan 14, 2015. He detailed the use of the database for shocks and SEP events.
- McGuire, R. E., D. Bilitza, R. Candey, R. Chimiak, J. Cooper, L. Garcia, B. Harris, R. Johnson, T. Kovalick, N. Lal, H. Leckner, M. Liu, N. Papitashvili, D. A. Roberts, Multi-Point Observations of the Inner Magnetosphere from the Van Allen Probes and Related Missions at NASA's Space Physics Data Facility (SPDF), Poster SM23B-4187, Fall 2014 AGU Meeting, San Francisco, CA, 2014.
- John Cooper presented remotely via WebEx at the splinter session "Harmonisation of SEP Data Calibrations" at the European Space Weather Week 11 conference in Liège, Belgium. He spoke on new scatterplot correlation functionality being implemented with the OMNIWeb services of the NASA Space Physics Data Facility (SPDF) in collaboration with the Virtual Energetic Particle Observatory (VEPO). John is Chief Scientist for SPDF and Principal Investigator for VEPO. Robert McGuire is SPDF Project Scientist. Natasha Papitashvili maintains OMNIWeb and created the new services as part of the SPDF-VEPO collaboration.
- John Cooper, Steven Sturner, Nikolaos Paschalidis, Richard Wesenberg, and Edward Sittler presented the talk "Natural Environmental Shielding Impacts on Missions to Extreme Radiation Environments" at the Second International Workshop on Instrumentation for Planetary Missions at GSFC during November 4-7, 2014. This talk addressed how Total Ionization Dosage (TID) is computed for Europa orbiter and flyby mission scenarios, and how moon body, ionospheric, and surface

topographic shielding can reduce the spacecraft shielding requirements.

- John Cooper presented the talk "Space Weathering Applications of the Virtual Energetic Particle Observatory" at the Fall science team meeting of the DREAM2 (Dynamic Response of the Environments at Asteroids, the Moon, and Moons of Mars) in Greenbelt. Led by William Farrell (695), DREAM2 is an interdisciplinary science team of NASA's Solar System Exploration Research Virtual Institute (SSERVI). Cooper leads the Virtual Energetic Particle Observatory (VEPO) in collaboration with Goddard's Space Physics Data Facility and DREAM2.
- John Cooper attended the Science Steering Group meeting of the Voyager mission at APL/JHU and spoke on progress and future plans for the Virtual Energetic Particle Observatory. Spectral flux and new scatterplot functions from Voyager and ACE mission data were demonstrated for 2010-2014.
- John Cooper presented the talk, "Space Weather Investigations Enabled by the Virtual Energetic Particle Observatory," to the SEP Intercalibration Workshop as part of the Space Weather Workshop in Boulder, CO. The particular value of VEPO was discussed for intercomparison of solar energetic particle data sets for the purpose of identifying and correcting calibration anomalies was discussed. So-called "reservoir events" after the peak phase of long duration SEP events, when flux spectra throughout the inner heliosphere are most similar even at widely separated spacecraft, were noted as ideal times for this purpose.
- John Cooper participated as co-author in the presentation, “Local Topographic Shielding and Radiation Shadows from Electron Irradiation on Europa” by Terry Hurford at the recent "Workshop for Habitability of Icy Worlds." His contribution is on modeling of surface irradiation fluxes as functions of surface position and local horizon angle for Jovian magnetospheric electrons at the orbit of Europa. This work can also be applied at higher altitudes to modeling of mission dosages for orbiter, flyby, and lander spacecraft at Europa

III. Summary.

The major milestone for year 1 involves procuring hardware and the modeling of a single event out to 1 AU has been completed and the team is preparing delivery of modules for the CCMC. The team is in the process of writing up three papers in which models of separate CMEs and energetic particles out beyond 1 AU are being performed. The C-SWEPA team has exceeded the milestone in the modeling of SEP events, CMEs and the analysis of observations in the remarkable mini-maximum of solar cycle 24.

The team is now gearing up for more extensive analysis of model results and comparison with observations. The C-SWEPA team has been extremely productive over the course of 2013-2014 with **19 outstanding publications** and presented **29 talks** covering a broad array of topics from the modeling of CMEs to the effects of energetic particles and galactic cosmic rays. The team has hit the ground running and we anticipate another highly productive year.